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Applicability of turbulence measurement technology to small-scale plankton studies

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ABSTRACT: This article contains the author's personal thoughts and prejudices about present techniques for turbulence measurements, and the limitations of these techniques for solving problems in physical–biological interactions.

KEY WORDS: Turbulence · Physical–biological interactions

Small-scale turbulence and mixing are fundamental in the early life stages of oceanic creatures. Mixing is accomplished by molecular diffusion that 'diffuses' away gradients. Turbulence is the stirring process that tends to increase gradients and increase the interfacial area over which these gradients occur (Eckart 1948). Turbulence also increases the contact rate between predator and prey (Rothschild & Osborn 1988). Furthermore, turbulence induces behavioral responses in some organisms. There is a rich body of literature concerning the effects of turbulence on predator–prey interactions and on survival of planktonic, early life stages.

Here, I briefly review some of what is known about turbulence in the ocean, consider what needs to be better delineated, and consider how to measure turbulence and planktonic response simultaneously.

What is turbulence?

It is more appropriate to say the flow is turbulent rather than the fluid itself is turbulent. A turbulent flow has certain characteristics: the motion is random, it is 3-dimensional, it contains vorticity (i.e. $\vec{\omega} = \nabla \times \vec{u} \neq 0$ where the vorticity, $\vec{\omega}$, is the curl of the velocity, $\vec{u}$, and is denoted as the vector cross product of the gradient operator, ∇, with the velocity vector), and kinetic energy is dissipated. The turbulent motion can transport heat, salt, and other properties. It tends to increase the transport (observable at large scales) above that due to molecular diffusion alone. Experience has shown that a useful parameter for scaling the intensity of small-scale turbulence is the dissipation rate, ε, which is the rate at which kinetic energy is dissipated by viscosity and converted to heat.

How do we observe turbulence in the ocean?

Hot films and shear probes

An excellent review on the measurement of small-scale, turbulent, velocity fluctuations in the ocean is given by Lueck et al. (2002). The modern era of small-scale turbulence measurements in the ocean began with the pioneering work of Grant et al. (1962). They used a towed body with a hot film anemometer to measure the turbulent velocity fluctuations to scales of millimeters. This sensor measures variations in the heat transfer between a hot film and the adjacent boundary layer. Variations in the flow modify the boundary layer and lead to variations in the heat flux. The probe is predominantly sensitive to fluctuations in axial velocity, i.e. in the direction of travel of the probe through the water. This system was moved from the towed body to the Pisces submersible (Gargett 1982), which is very difficult to operate, but produces data with the highest spatial resolution.

Vertical profiling of ocean turbulence is appealing because freely falling profilers are decoupled from the

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motion of the surface vessel. As well, they are moving across the horizontal layers in the ocean and should give a picture of the distribution of turbulence versus depth. Here, the velocity sensor of choice is the airfoil probe, developed by Siddon & Ribner (1965) and modified to work in the ocean by Osborn (1972). This sensor responds to the water motions that are transverse to its relative motion through the water. It is used on free-fall profilers, autonomous underwater vehicles, submersibles, expendable profilers, and gliders. Again, Lueck et al. (2002) have provided a review of the systems.

Hot films and airfoil probes have one great advantage—their output can be differentiated electronically. Since it is the spatial gradients of the velocity that are used to calculate the dissipation rate, the variance of the shear spectrum can be used to directly estimate the dissipation rate. While the airfoil probe is much easier to operate and more robust than the heated probes, it has limited spatial resolution due to its finite size. For many oceanic applications this effect can be removed spectrally (Macoun & Lueck 2004), but when we want to look in detail at the velocity variations with scales smaller than a centimeter or so, spatial averaging by the probe is a problem. Unfortunately, this is the size regime in which many interesting predator–prey interactions take place.

Acoustic techniques

There are a variety of acoustic velocity sensors that have been developed over the years (for a good introduction to the principles and the capabilities of small-scale measurements see Lhermitte [1981, 1983] and Lhermitte & Lemmin [1993]). All rely on the Doppler shift of the sound frequency as it is reflected by particles (and other sources of variations in the speed of sound). These probes are very useful because they can profile and can sample remotely, without intruding into the flow. There is a trade off between spatial resolution (which requires high frequency) and range (which decreases with increasing frequency). Since these sensors measure velocity, and cannot measure velocity gradients directly, the dissipation rate is generally estimated from fitting the velocity spectra to, so-called, 'universal shapes'.

Particle image velocimetry and particle tracking velocimetry

Particle image velocimetry (PIV) involves the illumination of a thin sheet of fluid with 2 flashes of a laser. The displacement of groups of particles in the flow, between the 2 exposures, is determined from the correlation of small subsets (e.g. 64 pixels by 64 pixels) of the image with the entire imager (2000 pixels by 2000 pixels). The displacement and time interval are used to infer the velocity of the fluid in the plane of the light (Bertuccioli et al. 1999, Doron et al. 2001, Nimmo Smith et al. 2002, 2005). The data consist of 2-dimensional maps of the velocity vectors (projected onto the plane of the light sheet), with each vector based on the average of several particles.

Particle tracking velocimetry (PTV) differs from PIV in that individual particles are tracked using continuous lighting and a continuously running video camera. Examples from the system of Nimmo Smith can be seen at www.coastalprocesses.org/. Like PIV this system depends upon the particles following the motion in order to infer the flow from the displacement of the particles.

Larger scale estimates of ε

There are 3 approaches to estimating the dissipation rate of kinetic energy that do not rely on small-scale velocity measurements. Dillon (1982) shows that the Thorpe scale, the root mean square displacement needed to reorder a measured density profile to produce a density profile that appears statically stable, is comparable to the Ozmidov scale $L_z = (\varepsilon/N^3)^{1/2}$, where ε is the kinematic energy dissipation rate in m^2 s^{-3}, and N is the Brunt–Vaisala frequency in radians per second. This enables estimation of the dissipation rate from well-resolved density profiles (or sometimes temperature profiles). This approach involves no measurement of velocity fluctuations, although it does involve small-scale measurements of the scalar field.

The second approach measures the turbulent eddies that contain kinetic energy (Gargett 1999). The idea is that almost all of the kinetic energy is at larger scales, characterized by a spatial scale L, and that this energy cascades to smaller scales where it is dissipated. The dissipation rate is the kinetic energy (estimated as U^2, where U is the speed associated with the turbulence at the larger spatial scales) divided by the eddy time scale (L/U) and hence $\varepsilon \approx U^3/L$. This approach requires measurements of velocity fluctuations, but not on dissipation scales.

Finally, there is a technique that involves measuring one component of the temperature gradient and using Batchelor's (1959) theoretical spectrum to infer the dissipation from the shape of the temperature gradient spectrum. This involves a measurement of the small-scale temperature fluctuations; here, the spatial resolution of the sensors is most problematic and often not documented. Furthermore, the most definitive paper comparing predictions against measurements (Gargett 1985) strongly suggests the universal spectral shape is not found consistently in the ocean. For the problem of biological interactions, where we are really interested in the details of the small-scale velocity fluctuations, inferring averaged values (i.e. dissipation) from a scalar quantity like temperature is probably inappropriate.

What do we know about turbulence in the ocean?

During the last 50 yr there has been a dramatic augmentation of the literature on oceanic turbulence. A recent compilation, in book form, by Thorpe (2005) covers our present understanding of oceanic turbulence, over a wide range of spatial scales.

Vertical distribution

In the upper ocean (from the surface to the pycnocline) turbulence is forced by surface cooling, wind stress, and energy from breaking waves. The turbulence is redistributed by convection, Langmuir circulation, and large-scale vortical motions. Below the level of the wave troughs, the turbulence often scales with the 'law of the wall,' $\varepsilon = u_*^3/\kappa z$, where ε is the dissipation, u_* is a velocity-scaling parameter derived by taking the square root of the ratio of the wind stress to the water density, κ is the Von Karmen constant ~0.4, and z is the depth below the water surface. There is a surface layer of enhanced dissipation between the crest and troughs of the waves. The energy for this dissipation is derived from the surface waves (Agrawal et al. 1992). Cooling of the sea surface drives convection, and dissipation can be calculated from buoyancy flux (Shay & Gregg 1984).

There are large structures in the upper layer. Langmuir cells align (almost) with wind direction and redistribute the turbulence and bubbles vertically (Thorpe et al. 2003a,b). There are also large-scale vortices aligned perpendicular with wind direction that produce temperature ramps and redistribute turbulence throughout the upper layer (Thorpe et al. 2003a). In addition, recent measurements with a submersible in Lake Geneva (Ozen et al. 2006) have revealed organized structures forcing turbulence up from the bottom of the mixed layer/thermocline. The interactions between these 3 mechanisms are unknown.

The thermocline contains layers of turbulence with vertical scales of meters and horizontal scales of hundreds of meters or more. These patches seem to have time scales of many hours and are likely associated with shears from inertial motions and internal waves. Bulk averages of dissipation seem to increase rather than decrease with stratification, $\varepsilon \propto N$ or N^2. The most likely explanation is the increase in internal wave energy with increasing stratification. Below the thermocline, a patchy distribution continues, with a general decrease in intensity with depth (and decreasing stratification).

Universal spectral shape

The pioneering work by Grant et al. (1962) verified the hypothesis of a universal shape for the turbulent velocity spectrum in the case of high Reynolds number, isotropic, and homogeneous flow. The −5/3 spectral slope predicted from the work of Kolmogorov was observed to separate the energy containing low wave number portion of the spectrum from the high wave number dissipation portion. Nasmyth (1970) provides an improved measurement of the shape, and the numerical values are found in Oakey (1982). Gargett et al. (1984) report a slightly different shape. Their measurements of all 3 velocity components show isotropy throughout the dissipation range, with an effect of stratification at lower wave numbers. When affected by buoyancy, the low wave number portion of the velocity spectrum follows a universal shape that can be nondimensionalized with buoyancy parameters.

The peak of the dissipation spectrum is at $k \approx 0.2\ k_s$, where $k_s = (\varepsilon/\nu^3)^{1/4}$ is the Kolmogorov wave number in radians per meter and ν is the kinematic viscosity. The exact numerical value depends on whether a lateral or axial velocity component is being considered. The wavelength corresponding to the peak of the dissipation spectrum is $\lambda = 2\pi/k_s \approx 10\pi\eta$, where $\eta = (\nu^3/\varepsilon)^{1/4}$ is the Kolmogorov length scale. At separations associated with this portion of the spectrum, the relative motion between particles is a viscous-straining motion. The Reynolds number at these scales is ≤1.

For biological interactions, a paper by Yamazaki & Lueck (1990) has shown a lognormal distribution for dissipation rates when averaged over scales substantially smaller than patch size, but larger than 3η. Particles with separation smaller than 3η are essentially in the same strain field. Theirs is the only paper to my knowledge that considers the details of shear at small scales. The interesting point is that average dissipation, over distances from 0.5 m to several meters, does not represent the instantaneous strain associated with predator–prey interactions over the time scale of those interactions. The time scale is related to the Kolmogorov spatial scale, $\tau = \left(\frac{\nu}{\varepsilon}\right)^{1/2}$, which is an estimate of the lifetime of the eddies at that scale.

PIV measurements of spectra

Recent measurements with PIV in the bottom boundary layer of the coastal ocean have given us results completely different from those obtained via hot films and airfoil probes. The data are time series, at a fixed location, of 2-dimensional vector maps of flow, with resolution almost to the Kolmogorov scale (Bertuccioli et al. 1999, Doron et al. 2001, Nimmo Smith et al. 2002, 2005, L. Luznik et al. unpubl.).

The measurements have been done in the bottom boundary layer of the coastal ocean, which is not the same oceanographic environment usually sampled with hot films and airfoil probes. There are several results from the present work that have significant impact on understanding turbulence in the coastal ocean and the impact of turbulence on predator–prey interactions. The measurements (L. Luznik et al. unpubl.) reveal that turbulence (1) appears to be anisotropic at all scales, (2) shows a Reynolds number effect on spectra, (3) does not fit universal shape, and (4) in some components, has more high wave number energy than expected.

Some conclusions about turbulence at small scales

Measurements to date do not really provide the information needed to thoroughly understand the role of turbulence on predator–prey interactions because (1) measurements of turbulent motions on scales of centimeters and smaller are really quite limited and (2) the temporal and spatial variability of the intensity is not well known.

Since the spectrum is not always universal or isotropic at dissipation scales, we cannot reliably predict the small-scale distribution of shear based on larger scale estimates of the dissipation rate.

Way forward

To truly understand the role of turbulence in early life stages, we need to observe the interactions and reactions that occur in conjunction with turbulent motion. Perhaps this can be done in laboratory experiments with freely moving organisms and realistically generated turbulence. However, while many laboratory results to date have been quantitative and performed with well-documented procedures, they represent environments never encountered by man or beast. It is unclear whether these results can be applied to the oceanic regime. Hence, observations must be made *in situ*: in the ocean, under realistic conditions. The requirement for such studies is that the organisms, their motions and actions, as well as the water motion be sampled simultaneously. The combination of holography and PIV offers the technology to accomplish this task. By making repeated holographic images with a digital camera, it is possible to track predators, prey, and smaller particles that follow the motion of the water.

Malkiel et al. (2003, 2005, 2006a,b), Pfitsch et al. (2005), and Sheng et al. (2006) describe the development and use of such a system. Further details are available at www.me.jhu.edu/~lefd/shc/shc.htm.

Holography has the advantage of resolving particles over a wide range of sizes. The interference pattern of the coherent light that makes the hologram spreads out the information from particles that are smaller than individual pixels in the digital camera so that they can be registered and reconstructed in the later analysis. Thus, the system can record dinoflagellates and copepods and resolve both.

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